AFRL-AFOSR-VA-TR-2015-0243

Development of Lattice Trapped Paramagnetic Polar Molecules

Subhadeep Gupta
UNIVERSITY OF WASHINGTON

06/23/2015
Final Report

Air Force Research Laboratory
AF Office Of Scientific Research (AFOSR)/ RTB
Arlington, Virginia 22203
Air Force Materiel Command

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
24-08-2015

2. REPORT TYPE
Final Performance

3. DATES COVERED *(From - To)*
15-03-2012 to 14-03-2015

4. TITLE AND SUBTITLE
BAA 2012: Development of Lattice Trapped Paramagnetic Polar Molecules for Quantum Simulation

5a. CONTRACT NUMBER

5b. GRANT NUMBER
FA9550-12-1-0051

5c. PROGRAM ELEMENT NUMBER
61102F

6. AUTHOR(S)
Subhadeep Gupta

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
UNIVERSITY OF WASHINGTON
4333 BROOKLYN AVE NE
SEATTLE, WA 981950001 US

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
AF Office of Scientific Research
875 N. Randolph St. Room 3112
Arlington, VA 22203

10. SPONSOR/MONITOR'S ACRONYM(S)
AFRL/AFOSR RTB

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
A DISTRIBUTION UNLIMITED: PB Public Release

13. SUPPLEMENTARY NOTES

14. ABSTRACT
We have demonstrated optimized production and spatial manipulation of Li-Yb mixtures in a weak regime of interactions, as well as a first exploration of Yb as a bath or probe for a strongly interacting Fermi gas of lithium. We have explored interspecies collisional resonances in the system and found first evidence of Feshbach resonances in a mixture of alkali and alkali-earth-like atoms, using a novel ultracold heteronuclear system of ground and excited state atoms. This was done by exciting Yb into a metastable 3P2 state (Yb*), thus introducing anisotropy into the interactions with ground state Li, which in turn leads to broad Feshbach resonances. We have initiated the optical lattice setup for our experiment and demonstrated its operation in a one-dimensional geometry leading to an array of two-dimensional pancake traps. We have also produced heteronuclear molecules of ytterbium-lithium for the first time, using the technique of photoassociation. We produced such molecules in an electronically excited state, thus identifying an intermediate state to use for future transfer to the electronically ground molecular state using a Raman technique.

15. SUBJECT TERMS
Molecules, Paramagnetic

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			Subhadeep Gupta

Unclassified	Unclassified	Unclassified	UU	**PAGES**	**19b. TELEPHONE NUMBER** *(Include area code)* 206-616-9649

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18

DISTRIBUTION A: Distribution approved for public release.

Final Report (15^{th} March 2014 – 14^{th} March 2015)
Development of Lattice Trapped Polar Molecules for Quantum Simulation

In year 1 of the grant (15^{th} March 2012 - 14^{th} March 2013), we worked on optimized production and spatial manipulation of Li-Yb mixtures in a weak regime of interactions, as well as a first exploration of Yb as a bath or probe for a strongly interacting Fermi gas of lithium. These resulted in publications [1] and [2].

In the weak interactions regime, we achieved nearly pure ^{174}Yb Bose-Einstein condensates of about 2.5×10^5 atoms and 173Yb Fermi degenerate gases of about 10^5 atoms at $T=0.3T_F$ in single species experiments. We achieved a fast repetition rate of Yb condensate production to 10 seconds, with fewer numbers of 5×10^4 atoms in the BEC. For dual species experiments, Li is co-trapped and sympathetically cooled by Yb. By controlling the final depth of the evaporation ramp, we achieved simultaneous degeneracy, with atom numbers of few times 10^4 for each species. By sacrificing all of the coolant Yb though evaporation, we cooled to as low as 6% of the Fermi temperature in ^{6}Li. By keeping a small amount of Yb in the trap, we establish a system in which Yb may act as a probe of the ^{6}Li degenerate Fermi gas. The problem of differential displacement due to gravitational sag is inherent in any two-species experiment. Using a magnetic field gradient and taking advantage of the fact that ground state Yb has no magnetic moment, we demonstrated the elimination of this differential displacement between Li and Yb. In our case, the spatial overlap is optimized at 64G/cm, where the differential gravitational force on the two atomic masses is cancelled by the differential magnetic force [2].

We brought the Li-Yb system into a regime of strong interactions by tuning an external magnetic field in the vicinity of the broad Feshbach resonance between two lithium spin states at 834 Gauss. We studied the dynamics of Li Feshbach molecules in a bath of Yb atoms. In the unitary regime of the Feshbach resonance, the Li fermions displayed good collisional stability in the presence of the Yb bath making Yb a promising candidate for a bath or probe of strongly interacting Li fermions [1].

In year 2 of the grant (15^{th} March 2013 - 14^{th} March 2014), we initiated the optical lattice setup for our experiment and also created a new ultracold heteronuclear system of ground and excited state atoms. This resulted in publication [3].

Our optical lattice operates at the wavelength 1070nm. The light is generated by amplifying the output of a diode laser through a fiber amplifier (NuFern, 50W). At this wavelength the relative Stark shift between Li and Yb atoms U_{Li}/U_{Yb} is about 2. As a first demonstration, we implemented a 1D optical lattice using a single retro-reflected beam on a BEC of ^{174}Yb atoms. The beam waist was 90μm, yielding a peak lattice depth of 8.5μK per Watt for ytterbium. For a short pulse of length 10μs, we observed the Kaptiza-Dirac diffraction of the BEC into several momentum states separated by 2 units of lattice recoil. If the lattice was adiabatically turned on, we observe healthy lifetimes of several seconds for atoms trapped in the resultant array of 2D pancake traps. The needed upgrades to implement higher dimensional optical lattices have also been initiated. We split the output of the fiber amplifier into three parts and sent each through a separate acousto-optic modulator (AOM). The three resultant beams will be fiber-coupled to the vacuum chamber. Each lattice dimension is set up for retro-reflection. The AOMs serve to frequency shift each beam differently, avoiding interference effects between dimensions. The AOMs are also used for intensity stabilization. We expect to extend our 1D lattice to a 3D lattice soon and observe the Mott-insulator (MI) transition in Yb as a first test.

We prepared a new mixture of internal states to explore strong interactions in the Li-Yb system. By exciting Yb into a metastable $^3P_2$ state (Yb*), we introduced anisotropy into the interactions with ground state Li, which in turn is predicted to lead to broad Feshbach resonances. We prepared this novel ultracold mixture and began assessment of its inelastic properties as a function of magnetic field in order to harness the inherent anisotropic interactions [3].

In year 3 of the grant (15th March 2014 - 14th March 2015), we completed an assessment of the anisotropic interactions in the Li-Yb* system using a mixture of the m_J=-1 state in ^{174}Yb ($^3P_2$) and the lowest Zeeman state in ^{6}Li. of the two species. Our results together with theoretical support from Svetlana Kotochigova's group at Temple University provide evidence for a Feshbach resonance due to anisotropic interactions at a field of 450 Gauss. Feshbach resonances have previously not been observed between alkali and alkaline-earth-like atoms. These findings were reported in publication [4].

We also produced heteronuclear molecules of ytterbium-lithium using the technique of photoassociation. Thus far we have produced such molecules in an electronically excited state, thus identifying an intermediate state to use for transfer to the electronically ground molecular state using a Raman technique. These results will form part of a future publication.

Finally, we have also substantially upgraded our optical trapping and related cooling techniques and improved atomic number (and thus experimental signal/noise) by more than one order of magnitude in experiments producing quantum degenerate mixtures of lithium and ytterbium. The experimental stability and cycle time are also significantly better. These developments bode well for all our future experiments on this system.

Three students (Anders Hansen, Alexander Khramov, William Dowd) obtained their PhDs working on different aspects of our Li-Yb experiment during the course of this grant.

The following publications were supported by this grant:

[1] A. Khramov, A.H. Hansen, A.O. Jamison, W.H. Dowd, and S. Gupta: *Dynamics of Feshbach Molecules in an Ultracold Three-Component Mixture.* Phys. Rev. A. **86**, 032705 (2012).

[2] A. Hansen, A. Khramov, W.H. Dowd, A.O. Jamison, B. Plotkin-Swing, R. J. Roy, and S. Gupta: *Production of quantum degenerate mixtures of ytterbium and lithium with controllable inter-species overlap.* Phys. Rev. A. **87**, 113615 (2013).

[3] A. Khramov, A. H. Hansen, W. H. Dowd, R. J. Roy, C. Makrides, A. Petrov, S. Kotochigova, and S. Gupta: *Ultracold heteronuclear mixture of ground and excited state atoms.* Phys. Rev. Lett. **112**, 033201 (2014).

[4] W.H. Dowd, R. J. Roy, R. Shrestha, C. Makrides, A. Petrov, S. Kotochigova, and S. Gupta: *Magnetic field dependent interactions in an ultracold Li-Yb($^3P_2$) mixture*. New Journal of Physics **17**, 055007 (2015); Special Focus Issue on New Frontiers of Cold Molecules Research.

1.

1. Report Type

Final Report

Primary Contact E-mail
Contact email if there is a problem with the report.

deepg@uw.edu

Primary Contact Phone Number
Contact phone number if there is a problem with the report

206-604-9582

Organization / Institution name

University of Washington

Grant/Contract Title
The full title of the funded effort.

Development of Lattice Trapped Paramagnetic Polar Molecules for Quantum Simulation

Grant/Contract Number
AFOSR assigned control number. It must begin with "FA9550" or "F49620" or "FA2386".

FA9550-12-1-0051

Principal Investigator Name
The full name of the principal investigator on the grant or contract.

Subhadeep Gupta

Program Manager
The AFOSR Program Manager currently assigned to the award

Tatjana Curcic

Reporting Period Start Date

03/15/2012

Reporting Period End Date

03/14/2015

Abstract

We have demonstrated optimized production and spatial manipulation of Li-Yb mixtures in a weak regime of interactions, as well as a first exploration of Yb as a bath or probe for a strongly interacting Fermi gas of lithium. We have explored interspecies collisional resonances in the system and found first evidence of Feshbach resonances in a mixture of alkali and alkali-earth-like atoms, using a novel ultracold heteronuclear system of ground and excited state atoms. This was done by exciting Yb into a metastable 3P2 state (Yb*), thus introducing anisotropy into the interactions with ground state Li, which in turn leads to broad Feshbach resonances. We have initiated the optical lattice setup for our experiment and demonstrated its operation in a one-dimensional geometry leading to an array of two-dimensional pancake traps. We have also produced heteronuclear molecules of ytterbium-lithium for the first time, using the technique of photoassociation. We produced such molecules in an electronically excited state, thus identifying an intermediate state to use for future transfer to the electronically ground molecular state using a Raman technique. Finally, we have also substantially upgraded our optical trapping and related cooling techniques and improved atomic number (and thus experimental signal/noise) by more than one order of magnitude in experiments producing quantum degenerate mixtures of lithium and ytterbium. The experimental stability and cycle time are also significantly better. Currently we produce more than 2x10^5 atoms of each species in conditions of deep quantum degeneracy. Our Yb condensate number of > 4x10^5

is also the largest among numbers reported worldwide. These are all significant milestones for the development of lattice trapped paramagnetic polar molecules for quantum simulation.

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Extensions granted or milestones slipped, if any:

AFOSR LRIR Number

LRIR Title

Reporting Period

Laboratory Task Manager

Program Officer

Research Objectives

Technical Summary

Funding Summary by Cost Category (by FY, $K)

	Starting FY	FY+1	FY+2
Salary			
Equipment/Facilities			
Supplies			
Total			

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